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Piezoelectric Generators in the Energy Harvesting Systems

GRZYBEK Dariusz

AGH University of Science and Technology,

Faculty of Mechanical Engineering and Robotics, Department of Process Control,

30 Mickiewicza Av., 30-059 Krakow, Poland

dariusz.grzybek@agh.edu.pl

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Abstract. Piezoelectric generator is a device used to convert mechanical energy into electrical energy. The basic element of the generator is made from piezoelectric material in which electrical energy is created as a result of deformations caused by reactions of mechanical structure of the generator. The amount of obtained electrical energy depends mainly on the piezoelectric material used, construction of the generator as well as a type of the source of mechanical energy. Construction of the generator is adjusted to the type of the source of mechanical energy. In order to obtain electrical energy from mechanical vibrations, the most frequent solution is beam structure. Effective electric energy generation by the piezoelectric generators depends on the following main factors: piezoelectric material used, generator structure, electronic system of the control and storage of energy, and the generator size. Generated by piezoelectric generators electric energy, can be used to power of miniaturized electronic devices with low power supply demand. The goal may be monitoring of the structure or industrial processes in hardly accessible places or/and in systems requiring the use of a big number of sensors. It will make cutting the operating costs possible and allow to create the eco-friendly technology without waste discharged batteries.

Introduction

The number of publications on obtaining electricity from mechanical vibration [1] has been growing since early 21st century, with a focus on increasing the effectiveness of energy conversion due to relatively low efficiency of piezoelectric systems. Among the significant scientific works were papers by Sodano and Inman [2][3][4] in which particular emphasis was placed on using the piezolelectric generators as a source of power. The results of testing of a rectangular cross-section beam generator with the PZT-4H ceramic element pasted onto it were presented for instance in the paper by Roundy in 2004 [5]. In successive years, the development of piezoelectric generators has taken place in two main areas: optimization of the beam structure to increase strain in the piezoelectric material and using new or modified piezoceramic materials with composite structure which ensure greater flexibility and resistance to brittle cracking in comparison with classical piezoceramic materials. The optimization of the energy generation structure is implemented by a suitable choice of the generator beam shape [6] and/or size of generator [7] and by introducing additional components with geometry adapted to the source of mechanical vibration [8]. Due to the production and commercial availability of new or modified piezoelectric materials, the PZT ceramics used in the first generators [5] is replaced by composite materials [9][10] or thin layers with piezoelectric properties [11]. Among the composites, the most frequently used in the generators is Macro Fiber Composite (MFC) which contains the piezoceramic phase in the form of square cross-section fibers placed in the polymer matrix [12], and Piezoelectric Fiber Composite (PFC) in which the piezoceramic phase has the form of round fibers [13]. One of promising applications of the piezoelectric generators is the power of wireless sensors in the monitoring systems, in which sensors are mounted in hardly accessible places or which requiring the use of a great number of sensors. This article presents possibility of application of piezoelectric generators to power of wireless sensor nods consisting of commercial components.

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Piezoelectric material in the generators

First generators were built with the use of *piezoelectric ceramics*, particularly PZT [5]. PZT is a mixed crystal of titanate and lead zirconium with the general formula: (x)PbTiO3-(1-x)PbZrO3 [14]. One can manipulate with properties of piezoelectric ceramics PZT by the modification of the percentage content of particular compounds comprising mixed crystal, x=(0-1). It enables the production of ceramics PZT of different set of material constants e.g. PZT-5A, PZT-5H, PZT-5K and other. Monolithic ceramic material is however fragile and when subject to strong tensions, cracks could appear in it. *Piezoelectric composites* have more resistant to destruction resulting from significant deformations than monolithic ceramic material. Composites are materials build of piezoelectric ceramics PZT of different shapes, layers of adhesive, polymer film and appropriately formed electrodes. On bolt-on parts of these composite layers there are properly fitted electrodes. Composites used for constructing generators nowadays are: MFC (Macro Fiber Composite) and PFC (Piezoelectric Fiber Composite), constructed from two phases: piezoelectric ceramics and warp from polymer material [15].

The efficiency of energy conversion in piezoelectric materials is visible in the values of the electromechanical coupling coefficients k_{33} and k_{31} [16]:

$$k_{33} = \sqrt{\frac{d_{33}^2}{s_{33}^{(E)}\varepsilon_{33}^{(T)}}}, \quad k_{31} = \sqrt{\frac{d_{31}^2}{s_{11}^{(E)}\varepsilon_{33}^{(T)}}} \tag{1}$$

where: d is a matrix of the piezoelectric constants [C/N], $s^{(E)}$ is a flexibility matrix determined for constant value of the electric field (m2/N), $\varepsilon^{(T)}$ is a matrix of the material permittivity constants determined for constant values of stresses.

Constant k_{33} describes the efficiency of energy conversion for generators, in which electric induction is parallel to the stress. Constant k_{31} for generators, in which electric induction is perpendicular to the stress. The values of k_{33} and k_{31} for the most often used piezoelectric ceramics and MFC are presented in Table 1. The composites MFC have lower efficiency of energy converting than sinters of ceramic piezoelectric materials, but MFC can be used in generators creating big strain of the piezoelectric material.

Table 1. Material properties of piezoelectric ceramics and MFC [17][18]

Piezoelectric ceramics	Constant			
	d_{33} [C/N]	d_{31} [C/N]	k_{33} [-]	k_{31} [-]
PZT-5A1	$409 *10^{-12}$	$-176 *10^{-12}$	0,67	0,34
PZT-5H1	$620 *10^{-12}$	$-250 *10^{-12}$	0,72	0,35
PZT-5J1	$554 *10^{-12}$	$-234 *10^{-12}$	0,75	0,38
PZT-5K1	$870 *10^{-12}$	$-370 *10^{-12}$	0,75	0,40
MFC	$400*10^{-12}$	$-170*10^{-12}$	-	-

Structures of generators for energy harvesting from vibration

Typical structure is *cantilever beam* with an additional mass usually mounted on the unbounded end of beam (Fig. 1).

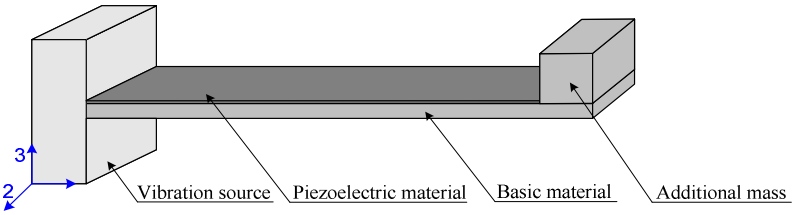

Fig. 1. Typical beam structure of the piezoelectric generator

The basic material used in beam structure is e.g. aluminium, stainless steel, brass. The piezoelectric material used most often is ceramics PZT or Macro Fiber Composite (MFC). The beam structure of the generator is usually achieved by gluing basic material with piezoelectric material. In literature the various modification of these structure are presented. In Fig. 2 exemplary modifications are shown:

- application of additional piezoelectric layers – e.g. *connected four cantilever beams* (Fig 2a),
- change of the beam shape – e. g. *M-shape beam* (Fig 2b).

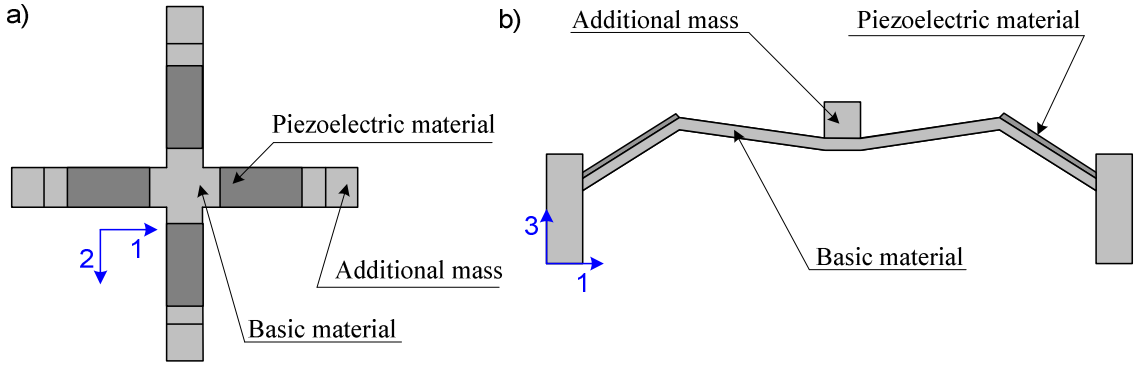

Fig. 2. Examples of modifications of beam structure of the piezoelectric generator [19][20]

The goal of such modifications is an increase of the generated electrical power. An effective electric energy generation also depends on the electronic system of recovered energy conversion. Three basic types of such electronic systems can be applied in piezoelectric generators: a system consisted only of the voltage converter AC/DC, a system consisted the converter AC/DC and the subsystem of the voltage optimization to the supplied receiver, a system consisted the converter AC/DC and the subsystem of the voltage optimization to the supplied receiver as well as the electric power amplifier [21].

Efficiency of energy conversion in generators

The field of potential applications of piezoelectric generators in energy harvesting systems is marked by the range of the electric power that can be generated by these generators. On the basis of published laboratory research results of piezoelectric generators one can state that the generated power doesn't excess several [mW]. The maximum power for selected piezoelectric generators with its dimensions are presented in Table 2.

Table 2. Exemplary values of the electric power for selected piezoelectric generators [9,18,19]

Structure of piezoelectric generator	Piezo-electric material	Dimension of piezoelectric material	Dimension of generator	Frequency of source vibration	Generated power
	-	[mm]	[mm]	[Hz]	[mW]
Cantilever beam	PZT	4 × patches: 25,4×50,8×0,254	114,3×50,8×1,27	29,5	1,4
Cantilever beam	MFC	2 × patches: 85×28×0,3	114,3×50,8×1,27	29,7	1,7
Connected four cantilever beams	PZT	4 × patches: 30×10×0,5	200×200×0,2	35,5	8,0
M-shaped beam	PZT	2 × patches: 25×25,4	220×25,4×0,254	14,5	2,6

On the basis of published research results three general factors influenced on the energy conversion efficiency can be enumerated:

- the greatest electric power is generated for a generator resonant frequency nearing to the driving frequency of the vibration source,
- the value of electrical power is depend on a strain of piezoelectric material in the generator. Hence generators with additional elements influencing on the increase of this strain generate more electrical power than typical cantilever beam generator,
- electrical power is proportional to a size of piezoelectric material used in generators [22].

Application of the piezoelectric generators in energy harvesting systems

One of the promising application of the piezoelectric generators is the power of wireless sensors, which can be applied in the monitoring systems of building and engineering structures e.g. in Structural Health Monitoring (SHM). The wireless sensors can be used to damages detection in bridges [23], masts, tall buildings, energetic infrastructure, aircraft, offshore oil platforms, naval ships, among many others [24]. The aim of piezoelectric generators application in such structure monitoring can be power the wireless sensors in hardly accessible places or/and in systems requiring the use of a great number of sensors (e.g. 70 nods in [23]). The ideal schema of the wireless sensor node, consist of piezoelectric generator, is presented in Fig. 3 (similar structures can be presented in literature e.g. [25]).

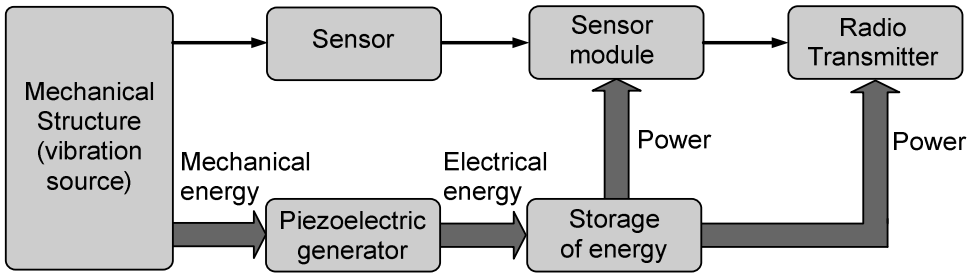

Fig. 3. Schema of wireless sensor node

Relatively not big values of generated power (Table 2.) considerably restrict the field of potential appliances to the supply of the miniaturized electronic devices with low power demand. Wireless sensors working on piezoelectric energy harvesting have to have lower values of power consumption than regular wireless sensor working on the batteries. Peak-power and standby current are the most important parameters of power consumption. The power consumption for selected commercial ultra low powered sensors are enumerated in Table 3.

Table 3. Exemplary low-powered regular sensors

Measured quantity	Company	Selected application	Power consumption
[-]	[-]	[-]	[mW]
Temperature	Texas Instruments	Temperature Monitoring	0,08
Acceleration	Analog Devices	Health devices	0,63
Humidity/ Temperature	Texas Instruments	Heating, Ventilation, Air Conditioning (HVAC)	2,75
Gas concentration	Cambridge CMOS Sensors	Monitoring of carbon monoxide	1,30

Radio transmitter (RT) is one of wireless nod elements, which have to be supplied by piezoelectric generator. Power consumption for exemplary commercial low-powered RT and wireless sensor with RT working on the batteries shown in Table 4.

Table 4. Exemplary ultra low-powered RT dedicated for wireless sensor nodes

Symbol/Company	Data rate	Power consumption
		[mW]
ZL70250/Microsemi	186 [kbit/s]	3,76
RF CMOS ISM/AnSem	128 [kbit/s]	2,60
1 GBPS ADC/Imec	-	1,60
IEPE-Link™/ Lord MicroStrain (sensor + RT)	1 [burst/10 minutes]	10,57
	1 [burst/hour]	2,50
	1 [burst/4 hour]	1,04

The structures of piezoelectric generators (presented in Table 2) enable the supply of wireless sensor (presented in Table 3) with RT (presented in Table 4), but the following two main conditions have to be fulfill: the frequency of vibration source would be equal to the generator resonant frequency and a control and storage system of the recovered energy should transfer the proper energy amount to supplied receiver (sensor and RT) in chosen periods. First condition is difficult to fulfill in the buildings, which vibrations are excited by natural processes e.g. wind. One of possible solution is a broadening of the generator frequency range by the application in generator structure several beams with various dimensions (each beams with other natural frequency).

Summary

On the basis of the literature study, which selected results were shown in the previous chapters, following conclusions are established:

- electric power generated by the piezoelectric generators from mechanical vibrations can't be enough to supply of the wireless sensor nodes, which enables the continues data transfer,
- electrical energy, generated by the piezoelectric generators, is enough to supply of the commercial low-powered micro sensors with commercial ultra low-power radio transmitters in the wireless nodes, which enables the periodical data transfer,
- the wireless sensor nod enabling the periodical data transfer powered by the piezoelectric generator have to have an electronic block to control and storage of recovered energy, which is needed to the transfer of proper energy amount to supplied receiver in chosen periods. Building of such block is still unsolved problem.

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